3-D Wave-Structure Interaction with Coastal Sediments – A Multi-Physics/Multi-Solution-Techniques Approach

Solomon C. Yim
Ocean Engineering Program
School of Civil and Construction Engineering
Owen Hall 220
Oregon State University
Corvallis, OR 97331-2302
Phone: (541) 737-6894 Fax: (541) 737-3052 E-mail: solomon.yim@oregonstate.edu

Award: N00014-06-1-0326

LONG-TERM GOALS

The long term goal of this research is twofold: (1) develop an advanced multi-physics model with a multi-numerical solution techniques approach to predict nonlinear dynamic behavior of impact burial and flow-induced motion of flexible structures (mines) and surrounding sediments (sand) in the marine environment; and (2) calibrate resulting models with experimental and field measurements. The predictive capability developed in this research will eventually be integrated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

OBJECTIVES

The deployment of mine via airdrop and subsequent sinking motion, burial and scour at sandy sea-bottom is of vital interest to the Navy. Until recently, no numerical codes can accurately model and simulate sea-surface impact, sinking motions and fluid-structure-sediment interaction and their effects on the overall burial behavior at the sea bottom are available. Major objectives of this research include assessment of the state-of-the-art analytical and numerical modeling capabilities, evaluation of the predictive capabilities of to numerical codes for coupled dynamic motions of submerged mines on a seabed in the marine environment, and further improvement of these codes to suit naval analysis, design and operational needs. The numerical predictive capability of these codes will be calibrated against experimental results and field observations.

APPROACH

The dynamic behavior of submerged mines and their surrounding sediments has been of interest to the Navy in recent years (Inman and Jenkins 2002). During 1960s-1980s, U.S. Naval scientists developed three burial prediction models that can be used for mine countermeasure tactical planning and for development of environmental support: impact burial, sand ridge migration, and wave-induced scour (Richardson and Briggs 2000). Capabilities for accurate modeling and prediction of motions of mines and their effects on the overall burial behavior at the sea bottom considering the detailed physics of the entire coupled mine-fluid-sediment-seabed “system” is needed. In this project, we focus our research efforts on two 3-dimensional (3-D) numerical codes: (1) LS-DYNA – multi-physics, multi-solution-techniques commercial code, and (2) an in-house research code with Navier-Stokes fluid and a bed-load sediment transport model.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **3-D Wave-Structure Interaction with Coastal Sediments - A Multi-Physics/Multi-Solution-Techniques Approach**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon State University,School of Civil and Construction Engineering,Ocean Engineering Program,Corvallis,OR,97331-2302**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The overall objectives of this research project will be achieved through the following tasks: first we will (1) conduct a thorough review of literature on mine-fluid-sediment interaction to determine the state-of-the-art analytical and numerical modeling capabilities; (2) evaluate the current predictive capability of LS-DYNA for coupled dynamic motions of submerged mines on a seabed in the marine environment; (3) identify development needs and further develop LS-DYNA for coupled fluid-structure-seabed interaction applications. Simultaneously, our group has been developing an in-house code using an alternative efficient approach. We will (4) use the in-house code to calibrate the computational efficiency of LS-DYNA. We will also (5) examine existing laboratory and field experiments available from ONR on motions of mines on seabed for numerical model calibration; (6) compare numerical predictions of resulting numerical modules developed with laboratory experiment and field data to validate and calibrate the numerical models for further evaluation; (7) conduct parametric study of characteristic burial and exposure times, and other parameters as appropriate; and (8) analyze and document research results.

WORK COMPLETED

LS-DYNA is an advanced nonlinear code which has one of the best solid mechanics, contact and impact models among commercially available ones, and has growing fluid mechanic features. It also has an excellent computational framework, and pre- and post-processing capabilities for our research group to take advantage of in developing additional modeling and analysis capabilities to address naval application needs. In the first two years of this project, we focused on the evaluation of current status and development of immediately needed capabilities of a multi-physics code LS-DYNA for impact burial and flow-induced motion predictions of mines and its surrounding sediments. During the last year we conducted an exhaustive study to understand and implement the smoothed particle hydrodynamics (SPH) method for the mine burial analysis applications. Currently we are in the process of comparing the arbitrary Lagrangian and Eulerian (ALE) and smooth particle hydrodynamics (SPH) formulations to evaluate their relative predictive capabilities.

We have examined several soil material models in LS-DYNA to determine if they are capable of modeling cohesionless soil. The three common laboratory tests that are performed to get the various material model parameters for the constitutive equations are (i) hydrostatic compression (ii) triaxial compression/extension and (iii) uniaxial strain. The material model parameters that can be calibrated to these data are used in the LS-DYNA soil constitutive models. A selected number of these models were reviewed as possible soil model candidates, from the simplest (material model 5) to the most complex (material model 25).

As a pure continuum approach is not able to capture the complex motion of the sand particles during the settling and burial of mines, the current focus relies heavily on a discrete approach technique called the smoothed particle hydrodynamics (SPH) method. The SPH method with various formulations can simulate different dynamic fluid flow problems including inviscid and viscous flows. Initially, the SPH technique available in LS-DYNA was applied to incompressible dynamic fluid flows**.** A series of numerical tests have been carried out to examine the ability and efficiency of the SPH formulations in simulating benchmark fluid dynamic problems. As an important step to achieve the goal of modeling the complex FSI phenomena like mine scour, it is imperative to learn the way SPH and FE couple in LS-DYNA. The buildup to the modeling of basic fluid dynamic problems using SPH method was furthered to understand the scour around a bottom mine. After the successful simulation of some of the benchmark fluid mechanics problems using a pure SPH-SPH coupling to SPH-FE coupling and testing the capability of LS-DYNA in handling the complex mine scour problems we are at a juncture where we are in the process of enhancing the code to suit for the present purpose. In order to model the scour around a mine it was necessary to understand how a pure SPH domain and SPH coupled with FE domain would model the benchmark problems.

We have developed a research code capable of computing the dynamic interaction among incompressible viscous air-water two-phase flow, movable rigid impermeable objects, and deformable permeable porous media using a finite difference model (FDM) with the volume of fluid (VOF) surface tracking, the body force type of immersed boundary (IB) method, and a bed load sediment transport model (Hur et al. 2007; Nakamura et al. 2008a, 2008b; Nakamura et al. submitted). The predictive capability of this numerical code is being calibrated against experimental results, field observations as well as LS-DYNA predictions.

RESULTS

To understand the extent to which LS-DYNA can model scour scenario and at the same time comprehend the capability of the software to handle various soil models, a wave generation experiment was conducted to simulate a simple experiment. The model contains the mine, fluid and a piston type wave generator which is defined in rigid shell elements. Geometry and dimension of the wave generating tank was so chosen to generate a 1.20m high wave from the sea level (Sunao Tokura 2005). The numerical wave tank has a non-reflective boundary condition at the far end of the solution domain in order to absorb the wave energy and prevent reflection. The other boundaries of the solution domain are along the side walls of the tank (impermeable no-slip boundary). Figure 1 shows the computational mesh. The tests were repeated for three soil models, however, as the other two tests produced results that are similar in nature, only the results from the first soil model is shown. Fluid density animation plots for the Soil and Foam model at various time steps are shown in Figure 2. The existing models are based on the Drucker-Prager soil models which are directly based on either the Mohr-Coulomb failure surface or the Modified-Mohr–Coulomb failure surface which cannot be used to properly understand the saturated sand behavior. The simulations thus far utilizes a continuum approach to model each of the fluid, sand, solid mediums using an Arbitrary Lagrangian and Eulerian (ALE) approach. As the use of ALE techniques is not sufficient to fully analyze the scour around the mine, a robust soil model is needed to fully capture the scour scenario. Apart from this an additional material characterization is needed to fully understand the capability of LS-DYNA in handling saturated sand behavior. The key for these kinds of modeling studies is a soil model that includes the pore pressure effects in the saturated sand and clearly none of the existing LS-DYNA geomaterial models include pore pressure into its effect. However, it has been found that a pure continuum approach is not sufficient to capture the complex motion of the sand particles during the settling and burial of mines. A discrete approach such as smooth particle hydrodynamics (SPH), which relies on the equations of state to represent the material behavior, is being investigated as a viable alternative. Retaining a similar wave generation experiment over a sand bed, a comparative study to understand scour scenario around a solid object (mine burial) will be conducted using the SPH method available in LS-DYNA.

The applications of SPH to coupled FSI problems can categorized in two different categories: (1) FE-SPH coupling; and (2) pure SPH domain with SPH-SPH coupling. We conducted a large number of simulations for a set of benchmark cases. In this report only selected simulation results using a pure SPH domain are shown. The usage of SPH ghost-particles to reduce the computational time for the fixed boundary particles can be shown using the Dam Break case in a tank for both fixed-rigid cylinder and a flexible cylinder (Fig. 3). It is important to note that with the use of SPH ghost particles the model behaves as 2-D which emphasizes the use of regular fixed boundary SPH elements for all the simulations. Fig. 4 shows the computational domain for the wave dissipation mechanism on a submerged mine. The modeling domain includes a wave making scenario with soil as the base. The wave tank is rectangular in shape and is built using SPH boundary particles. The waves are generated using a typical wave maker setup. The mine is rigid and it rests on the soil-water interface initially. The soil material used for simulation is the Mat-5 which is the Soil and Foam model. The gravity switch was initially set on for about 0.5 seconds before the waves for generated. Fig. 5 shows the wave generation at various time steps and the subsequent motion of the mine under wave dissipation. Fig. 6 shows the first run which treats soil as a water materiel (Null material) with a Gruniesen EOS. The density of a material was however set to that of the saturated sand. The subsequent runs involve modeling Soil using Mat-5 (Soil and Foam model) with varying densities of the mine deck (Fig. 7). Currently the implicit solver does not support SPH elements as it is used mostly for explicit applications. However, from the simulation results, we found that SPH can couple very well with FE through the contact algorithm. We are still actively working on the aspect where we treat the fluid domain into ALE (where the wave action is large) and FE for the bottom domain where it contacts the sand (which is pure SPH). With this setup we have a finer SPH mesh (slave) than the FE mesh (master) and any nodes to surface contact should work.

As an alternative to the LS-DYNA code, a 3-D numerical code capable of computing the dynamic interaction among incompressible viscous air-water two-phase flow, movable rigid impermeable objects, and deformable permeable porous media was developed using a finite difference model with the volume of fluid surface tracking, the body force type of immersed boundary (IB) method, and a bed load sediment transport model (Hur et al. 2007; Nakamura et al. 2008a, 2008b; Nakamura et al. submitted). The simulation of fluid flows is based on the large eddy simulation. Turbulent stress based on the dynamic two-parameter mixed model, surface tension force based on the continuum surface force model, resistant force (inertia force, and laminar and turbulent drag force) due to porous media, wave generation source and sink to generate Airy, Stokes, and solitary waves, and artificial damping force to prevent the wave reflection at the offshore and onshore boundaries are incorporated into continuity and Navier-Stokes (NS) equations. The multi-interface advection and reconstruction solver is used to track free surface locations. The motion of objects is computed using the body force type of IB method, in which the objects are represented using their volume fraction in each cell (Yuki et al. 2007). Artificial interaction force computed based on the volume fraction of the objects is incorporated into the NS equation to enforce specified boundary conditions on the surface of the objects. The bed load sediment transport is taken into account as the deformation of porous media. The volume fraction of the media in the NS equation is updated at each time step to couple the fluid motion and media deformation. The bed load sediment transport rate is computed using an empirical model given by a function of the Shields parameter (Engelund and Fredsøe 1976; Fredsøe and Deiggard 1992), and the sliding of the porous media with more than an angle of repose is computed in such a way that the equilibrium of force acting on sand particles is satisfied (Roulund et al. 2005). Figure 8 shows an example of computed dynamic interaction among periodic waves, a freely falling object slightly heavier than water, and deformable porous seabed composed of fine sand. The object is released as soon as the wave motion starts. The drop of the object induced strong vortices around the bottom edge of the object, resulting in erosion on the surface of the seabed. After the falling object reaches the seabed, the wave action causes the wave-directional oscillation of the object on the eroded seabed. As shown in the figure, the interaction among waves with air bubble entrainment, movable rigid impermeable objects, and erodible porous media can be computed. This model can be applied to a wide variety of phenomena on fluid-structure-porous media dynamic interaction in naval applications. The applicability of this model will be calibrated thoroughly by comparing numerical prediction with data obtained in experiment and field measurement.

IMPACT/APPLICATIONS

The advanced, state-of-the-art FE code LS-DYNA adopted in this project, when fully developed, will enhance the modeling, prediction, operation and control capabilities of the complex mine-fluid-sediment-seabed interaction in general and the numerical simulations of flow-induced mine burial impacts in particular. The 3-D numerical codes being developed will provide additional tools to calibrate and validate the accuracy of the numerical predictions of the modules with laboratory experiment and field data. A schematic diagram of ideal numerical models using domain decomposition with various numerical techniques for different domains of the coupled fluid-structure-soil interaction system is depicted in Figures 9 and 10 below. From the computational sketch it can be seen that the fluid domain followed by the structure and the sand can be modeled using four different computational methods. The fluid domain will be modeled using the fully nonlinear potential flow (FNPF) or the boundary-element method (BEM). Reynolds averaged Navier-Stokes (RANS) and the particle finite element method (PFEM) will be used in the water/mine/sand domain. Sand and the geomaterials around the sand will be modeled using the Smoothed Particle Hydrodynamics method (SPH). The resulting numerical predictive capability will be incorporated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

TRANSITIONS

Analysis and simulation capabilities developed in this research can be useful to the various units of the Navy pertinent to mine deployment, detection, burial clearance process studies.

RELATED PROJECTS

The analysis and simulation capabilities developed in this research will be incorporated into a companion project (N00014-07-1-0008) on the development of an overarching computational framework for analysis and prediction of dynamic motions of naval systems in the marine environment in arbitrary water depth.

REFERENCES

Engelund, F., and Fredsøe, J. “A sediment transport model for straight alluvial channels,” Nordic Hydrology, Vol. 7, pp. 293-306, 1976.

Fredsøe, J., and Deiggard, R. “Mechanics of Coastal Sediment Transport,” World Scientific, 1992.

Hur, D.-S., Nakamura, T., and Mizutani, N. “Sand suction mechanism in artificial beach composed of rubble mound breakwater and reclaimed sand area,” Ocean Eng., Elsevier, Vol. 34, No. 8-9, pp. 1104-1119, 2007.

Inman, D.L., and Jenkins, S.K. 2002. Scour and burial of bottom mines, a prime for fleet use. Interactive Oceanography Division, Scripps Institute of Oceanography, SIO Reference Series, 2-8.

Nakamura, T., Hur, D.-S. and Mizutani, N. “Mechanism of backfilling sand discharge from a gap under a vertical revetment,” J. Wtrwy., Port, Coast., and Oc. Engrg., Vol. 134, No. 3, pp. 178-186, 2008a.

Nakamura, T., Kuramitsu, Y., and Mizutani, N. “Tsunami scour around a square structure,” Coastal Eng. J., JSCE, Vol. 50, No. 2, pp. 209-246, 2008b.

Nakamura, T., Mizutani, N., and Yim, S. C. “Prediction of wave induced sediment transport and topographic changes around a structure,” J. Offshore Mechanics and Arctic Eng., submitted.

Richardson, M.D., Briggs, K.B. 2000. Seabed-structure interactions in coastal sediments. Proceedings of the 4th International Symposium on Technology and the Mine Problem. Naval Postgraduate School, Monterey, CA, 13-16 March.

Roulund, A., Sumer, M., Fredsøe, J., and Michelsen, J. "Numerical and experimental investigation of flow and scour around a circular pile," J. Fluid Mech., Vol. 534, pp. 351-401, 2005.

Sumer, M. "Mathematical modeling of scour: A review," J. Hydraulic Research, Vol. 45, No. 6, pp. 723-735, 2007.

Sunao, T., and Tetsuli, I. 2005. Simulation of wave dissipation mechanism on submerged structure using fluid-structure coupling capability in LS-DYNA. 5th European LS-DYNA users conference. 25-28.

Yuki, Y., Takeuchi, S., and Kajishima, T. “Efficient immersed boundary method for strong interaction problem of arbitrary shape object with the self-induced flow,” J. Fluid Sci. and Tech., Vol. 2, No. 1, pp. 1-11, 2007.

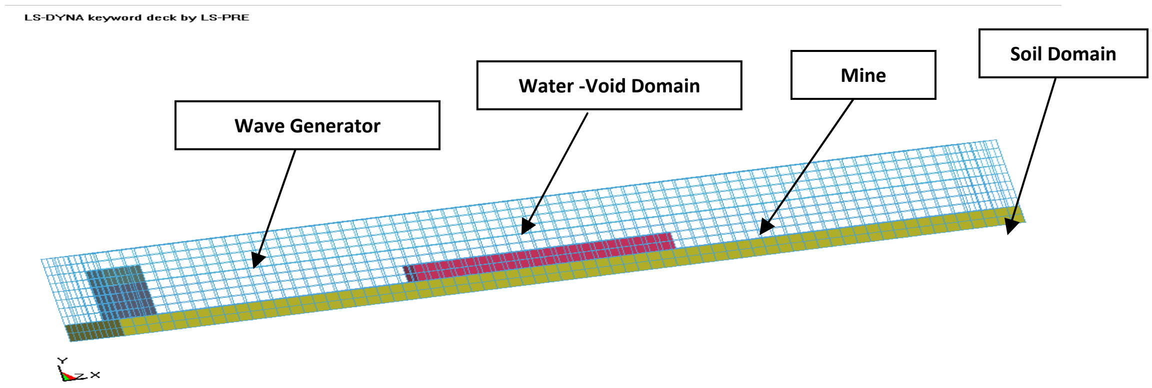

Fig. 1 The computation domain (Isometric View)

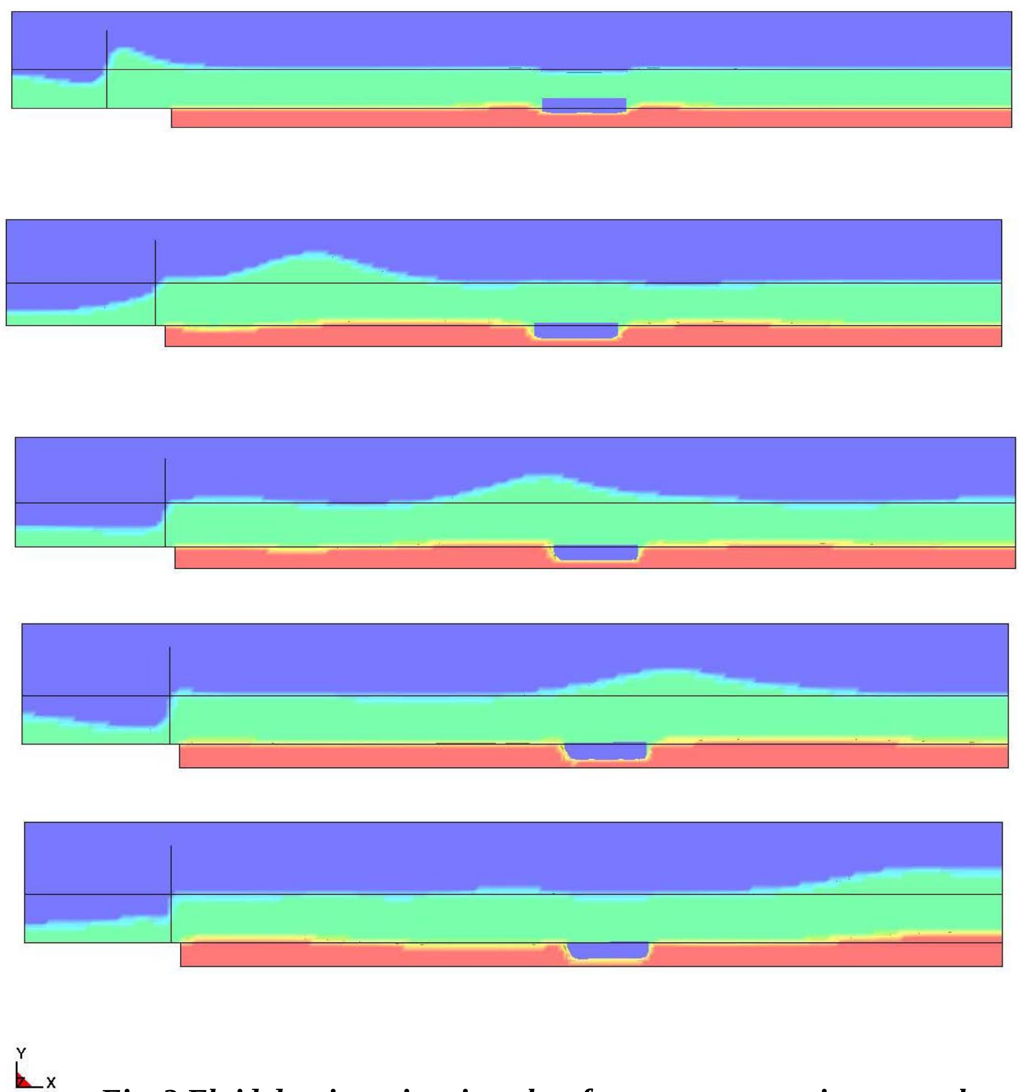

Fig. 2 Fluid density animation plots for wave propagation over a bottom mine at various time steps (Soil and Foam model)

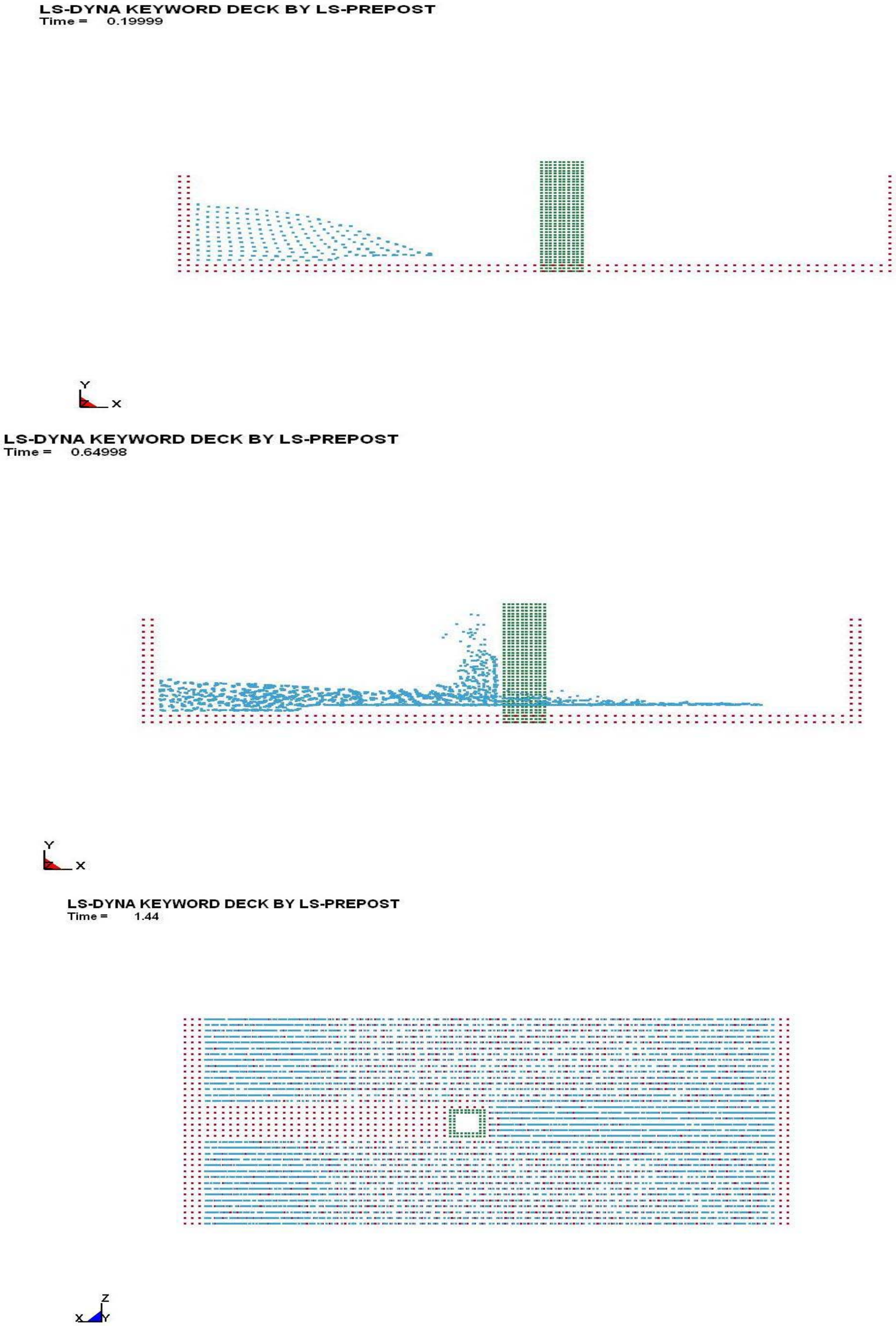

Fig. 3 Dam Break (cylinder fixed-SPH Ghost Particles)

[Top View: Model behaves as a 2-D case with the ghost particles in the lateral direction]

Modeling wave dissipation mechanism on a submerged mine-SPH

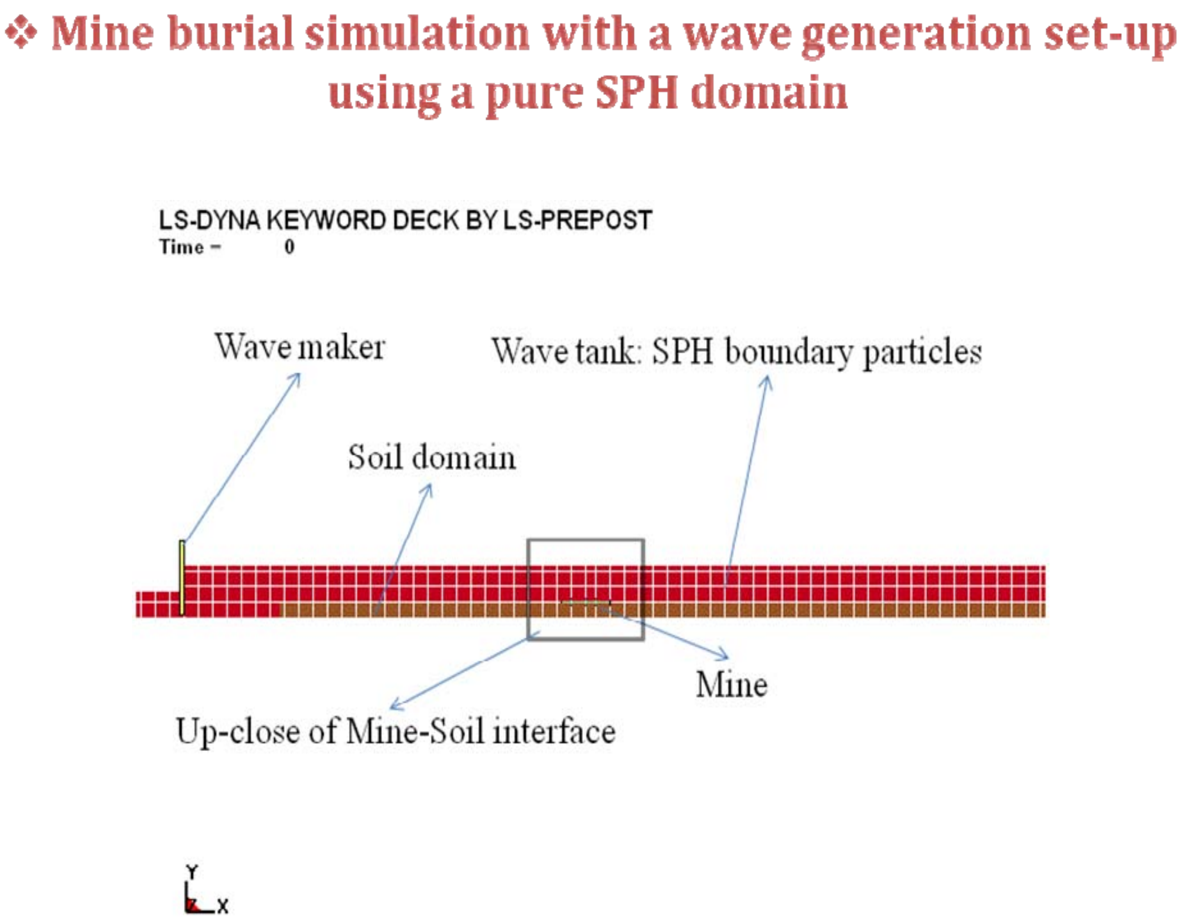

Fig. 4 Computational domain for the mine burial using SPH

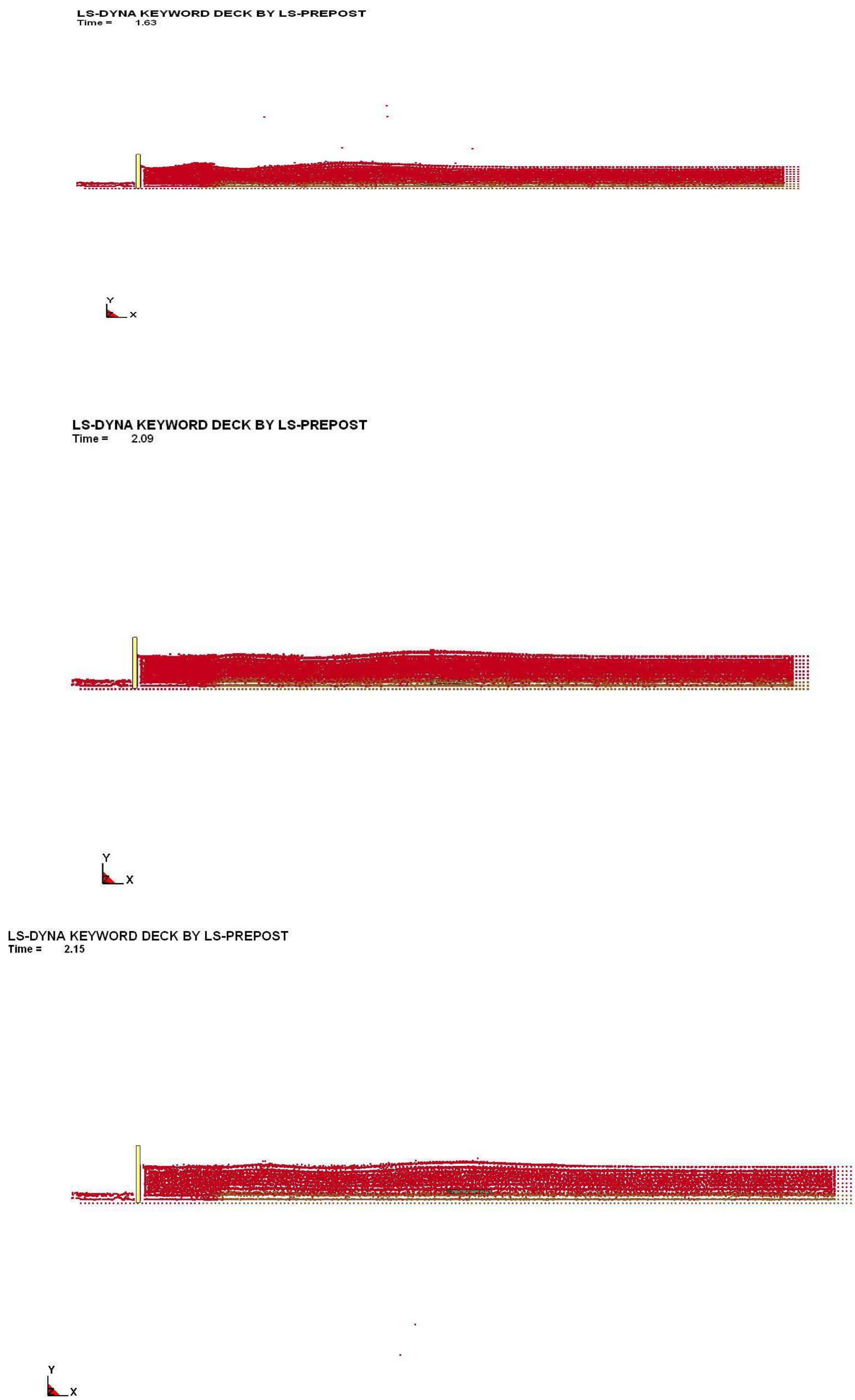

Fig. 5 Mine Burial simulation with a wave generation set-up using a pure SPH domain

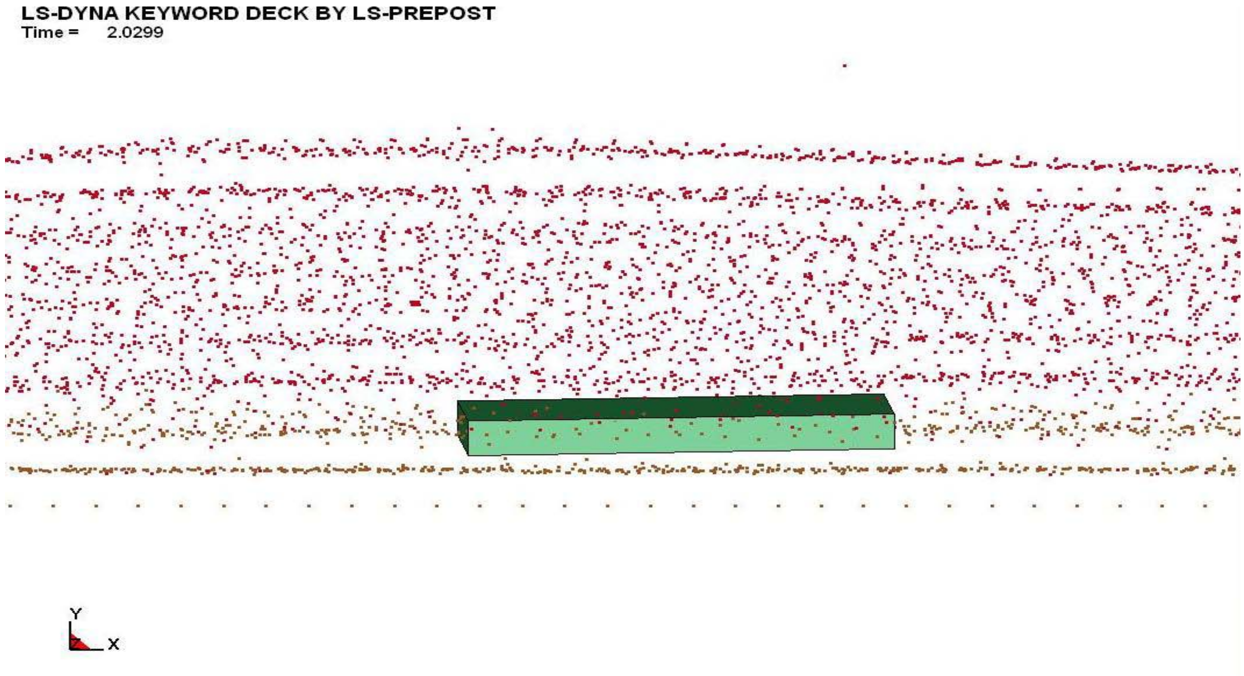

Fig. 6 Up-close of the soil water interface and mine burial mechanics

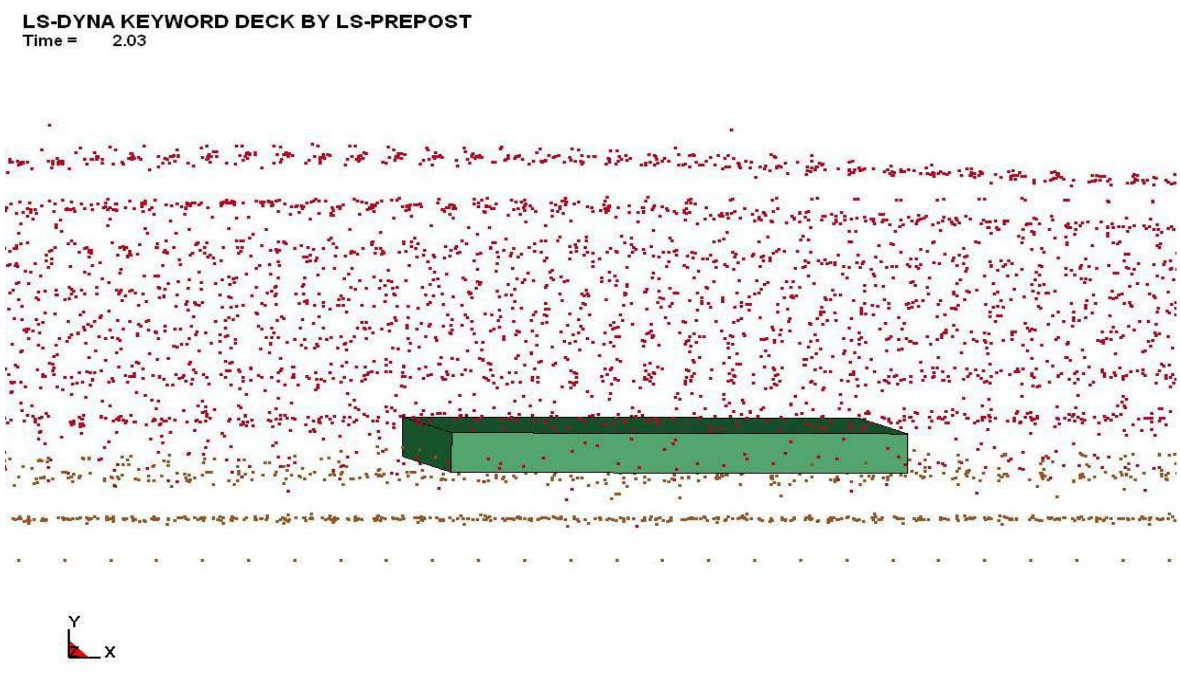

Fig. 7 Soil modeled with Mat-5 (Soil and Foam model) in LS-DYNA

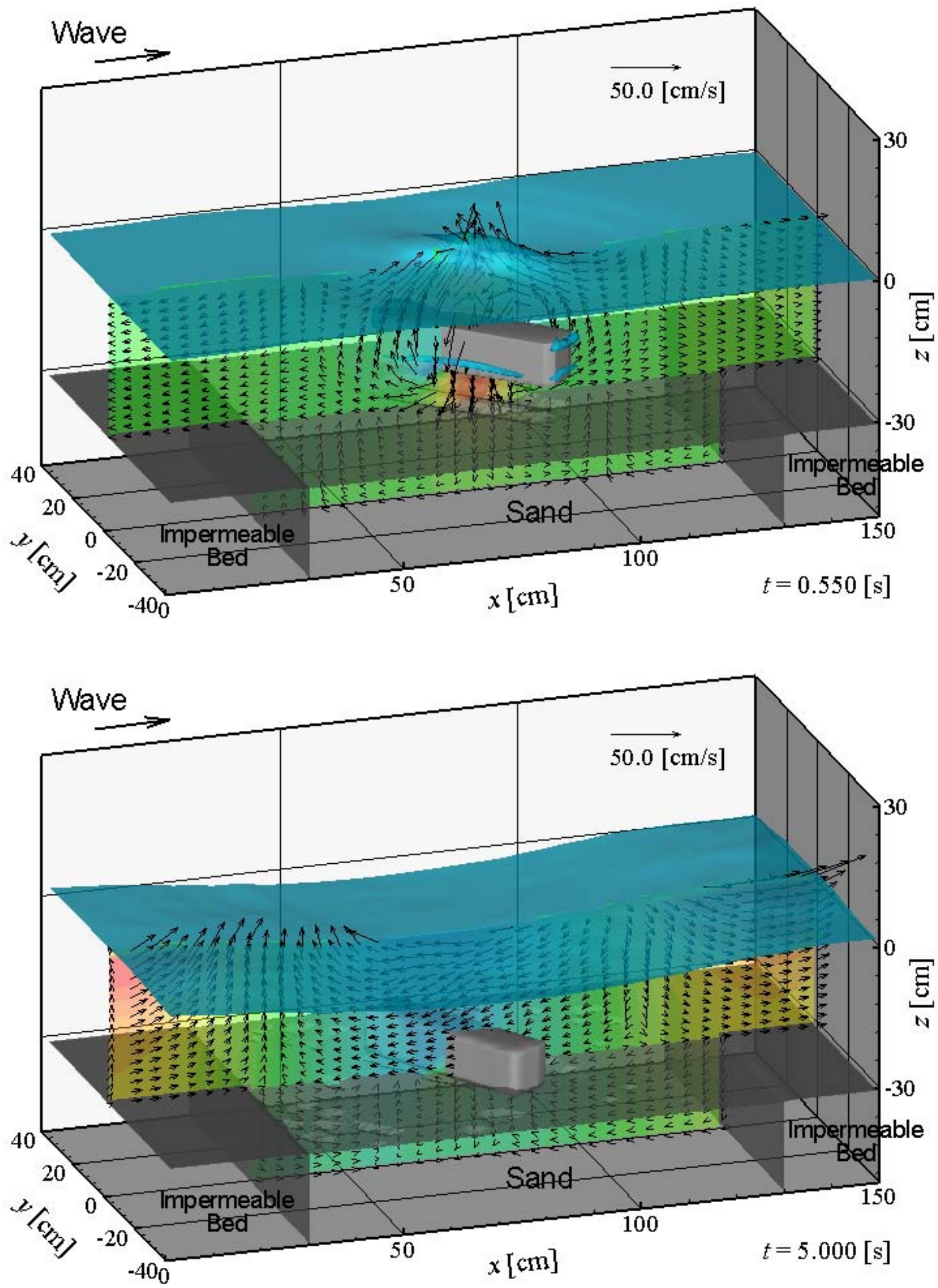

Fig. 8 Fluid-structure-sediment interaction in periodic waves (wave period: 1.0 s; wave height: 0.05 m; still water depth: 0.3 m), a freely falling rigid object (specific weight: 1.05), and deformable sandy seabed (median grain diameter: 0.2 mm)

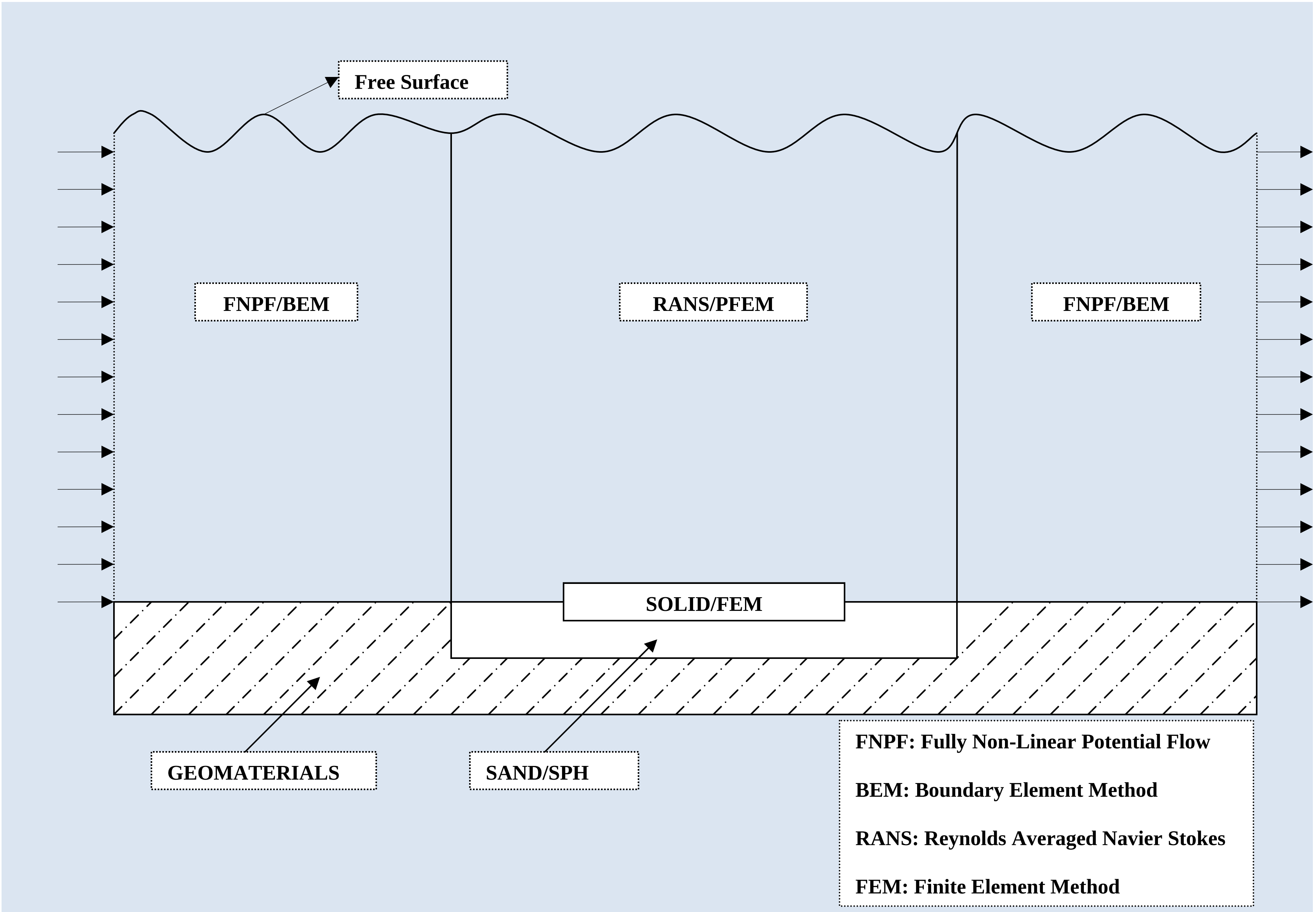

Fig. 9 Computation model (various methods that will be used) for the coupled Fluid Structure Interaction (FSI) problem

PUBLICATIONS

G. Cao, S.C. Yim, F. del Pin and G. Cook, “Particle Finite Element Solution to Arbitrary Lagrangian-Eulerian Reynolds Averaged Navier-Stokes Equations,” *International Journal of Numerical Method in Engineering*, (submitted).

G. Cao, S.C. Yim, F. del Pin and G. Cook, “A Particle Finite Element Solution for ALE RANSE Coupled Fluid-Structure Interaction Systems,” 27th Symposium on Naval Hydrodynamics, Seoul, Korea, Oct. 5-10, 2008.

Nakamura, T., Mizutani, N., and Yim, S. C. “Prediction of wave induced sediment transport and topographic changes around a structure,” *J. Offshore Mechanics and Arctic Eng.*, submitted.

S.C. Yim, D. Yuk, A. Naess and I-M. Shih, “Stochastic Analysis of Nonlinear Response of a Moored Structural System under Narrowband Excitations,” *Offshore Mechanics and Arctic Engineering*, ASME, Vol.130, Feb 2008, 011004, pp.1-7.

S.C. Yim, D. Yuk, A. Panizzo, M. Di Risio and P.L-F. Liu, “Numerical Simulations of Wave Generation by a Vertical Plunger Using RANS and SPH Models,” *Waterway, Port, Coastal and Ocean Engineering*, ASCE, Vol.134(3), May/June 2008, pp.143-159.

S.C. Yim, H. Lin, D.C. Robinson and K. Tanizawa, “Predictive Capability of a Fully-Nonlinear Potential Flow Model of a Fluid-Structure Interaction System,” *Offshore Mechanics and Arctic Engineering*, ASME, Manuscript No.OMAE-20056-1101, August 2008, pp.1-10.

S.C. Yim and D. Yuk and P.L-F. Liu, “Fluid-Structure Interaction Modeling Using RANS Equations,” *Ocean Engineering*, (submitted).